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11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Air Force position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This proposal was for acquisition of an advanced semiconductor device modeling system to characterize transistors, diodes and passive element from 45 MHz to at least 110 GHz to enable design and development of advanced electronic terahertz sensing systems based on both silicon and gallium-arsenide materials. The need for such systems is becoming increasingly urgent since sophisticated weapons and explosives require increasingly sophisticated detection technologies. Non-metallic varieties of these threats are especially important because they elude familiar metal-detecting portals. We have demonstrated in recent and comprehensive single-pixel studies that threats like these are readily detectable and even identifiable using broadband-pulsed signals in the microwave and millimeter-wave regime (1–1000 GHz). While traditional equipment for generating and detecting these frequencies has been hard to use, bulky and expensive, our unique all-electronic and monolithically integrated technology for generating and detecting these signals can now be applied to broadband spectroscopic imaging, detecting the reflection spectra of plastic weapons and explosives on human subjects.

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Objectives

This proposal supported acquisition of an advanced semiconductor device modeling system to characterize transistors, diodes and passive element from 45 MHz to at least 110 GHz to enable design and development of advanced electronic terahertz sensing systems based on both silicon and gallium-arsenide materials. The need for such systems is becoming increasingly urgent since sophisticated weapons and explosives require increasingly sophisticated detection technologies. Non-metallic varieties of these threats are especially important because they elude familiar metal-detecting portals. We have demonstrated in recent and comprehensive single-pixel studies that threats like these are readily detectable and even identifiable using broadband-pulsed signals in the microwave and millimeter-wave regime (1–1000 GHz). While traditional equipment for generating and detecting these frequencies has been hard to use, bulky and expensive, our unique all-electronic and monolithically integrated technology for generating and detecting these signals can now be applied to broadband spectroscopic imaging, detecting the reflection spectra of plastic weapons and explosives on human subjects.

In order to build such systems using foundry fabrication services, new device models are essential, since typical device models are extracted only up to frequencies of around 1 GHz. The system proposed will exceed this limit by two orders of magnitude, and enable competent design of compact, multi-pixel imaging and sensing systems in the terahertz (THz) regime.

This system has contributed directly to the development of such advanced imaging systems, and also supports the education and training of an entire generation of graduate students who will learn the principles of device measurement and modeling while applying the results to systems that can enhance security.

Status of effort

We have designed and built both devices (HBT and diode) using the 110 GHz parameter modeling and extraction system acquired with this DURIP support to realize a number of important circuits and sub-systems for THz spectroscopy:

- Diodes for phase shifters to enable coherent THz measurement systems
- MOS diodes for advanced nonlinear transmission lines
- Knowledge-On Foundry 60 GHz HBT Large Signal Model Parameter Extraction
- Four-bit prototype DAC (Digital to Analog Converter) running at 10GS/s
- High Speed Broadband Distributed Amplifier
- High instantaneous bandwidth VGA
- Broadband VGA
- 100 GHz Phase Shifter
- LNA (Low Noise Amplifier) Simulation and Fabrication
- Measurements of microfabricated traveling wave tube (TWT) structures

This report covers a sampling of the results we have achieved using this system.

Accomplishments/New Findings

1. MOS NLTL Design and Simulation

1.1. MOS NLTL Epitaxial Layer Design

Undoped GaAs caplayer, 50A
Undoped AlAs, 300A
N- GaAs layer, conc.=1e15, 1um
N+ GaAs buffer layer, conc.= 5e18, 1um
(100) N+ GaAs substrate

Fig. 1 MOS NLTL Epitaxial Layer Design

To achieve low-loss nonlinear transmission lines, we have been exploring MOS diodes on GaAs using the preferential oxidation of AlAs to create a quasi-native oxide layer (see layer design above). This enables nonlinear C-V behavior without forward-bias conductance, reducing loss. Simulations (below) indicate extremely nonlinear performance, which in turn promises good harmonic generation in shorter NLTLs, increasing efficiency.

1.2. MOS Varactor Device Simulation Using MEDICI

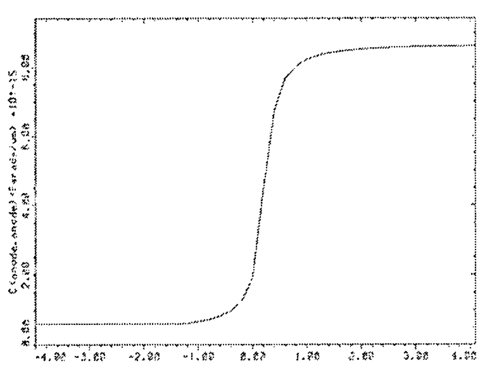


Fig. 2. MEDICI simulation of MOS varactor on GaAs

- GaAs with Al_2O_3 insulating layer
- Al_2O_3 allows higher power input and more nonlinearity
- Higher CV ratio and non conducting diode can be achieved

Status: waiting for revised epi layer to be delivered so measurement can commence.

2. Knowledge-On 60 GHz HBT Large Signal Model Parameter Extraction

2.1. GP (Gummel Poon) Model Parameter Extraction Using Agilent IC-CAP

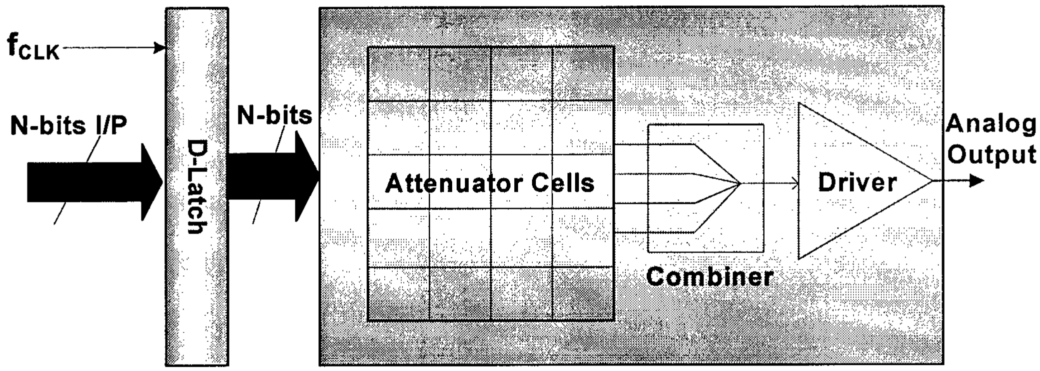
2.2. VBIC (Vertical Bipolar InterCompany) Model Parameter Extraction Using Agilent IC-CAP

2.3. Phillips MEXTRAM Model Parameter Extraction Using Agilent IC-CAP

Several different models were extracted from HBT structures fabricated by Knowledge-On. These were subsequently used in circuits described below.

3. Four-bit prototype DAC (Digital to Analog Converter) running at 10GS/s

3.1. Prototype DAC System Schematic



3.2. Prototype DAC ADS Simulation Result

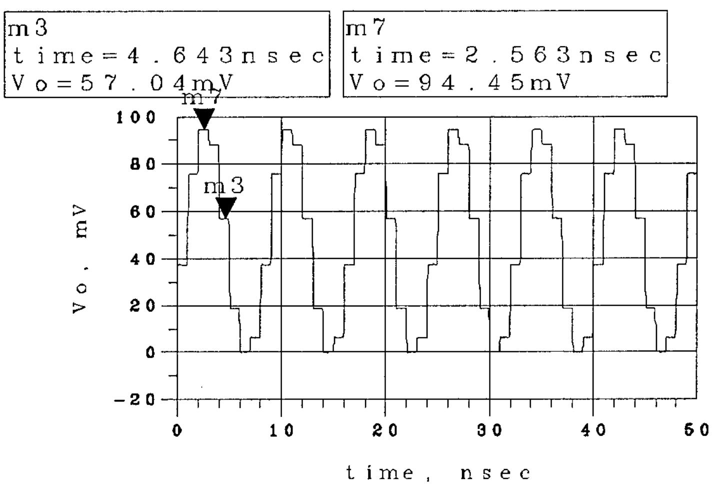
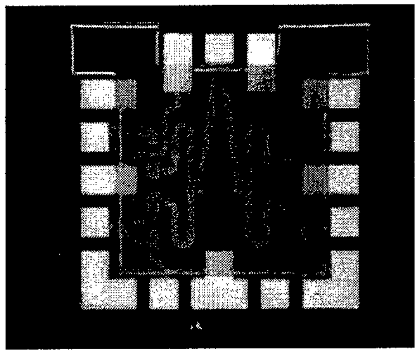


Fig. 4. Synthesized sine wave simulation from the DAC.

- Simulated sine wave is 125MHz at $f_o = 1/8*f_{clk}$ with 1GS/s input

3.3. Fabricated DAC Chip



3.4. DAC Measurement

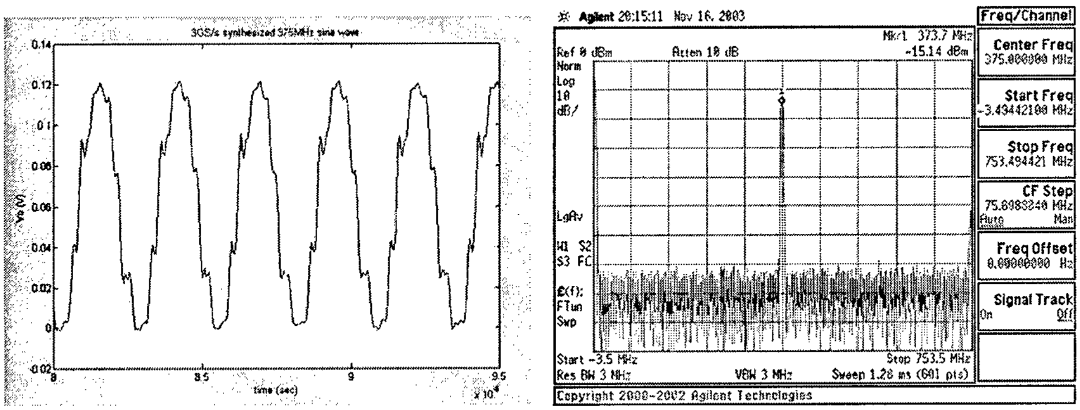


Fig. 6. Measured (synthesized) sine wave from DAC.

- Synthesized sine wave is 375MHz at $f_o = 1/8*f_{clk}$ with 3GS/s input.
- The spectrum analyzer shows 38dBc dynamic range between the fundamental signal and higher order harmonics.

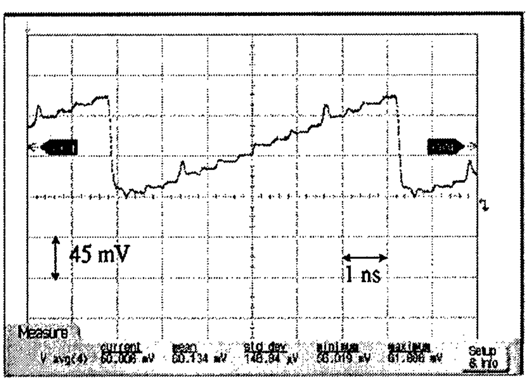


Fig. 7. Maximum INL measurement

- The maximum Integral Nonlinearity Error (INL) derived from this measurement is 2 LSB.

Status: project completed.

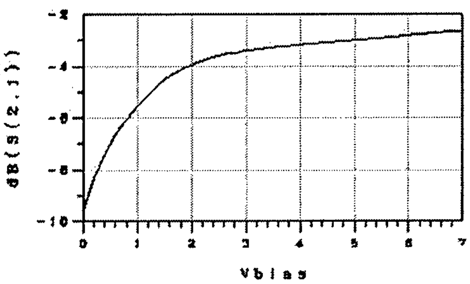
4. 100 GHz Phase Shifter

4.1. 100 GHz Phase Shifter Simulation Results

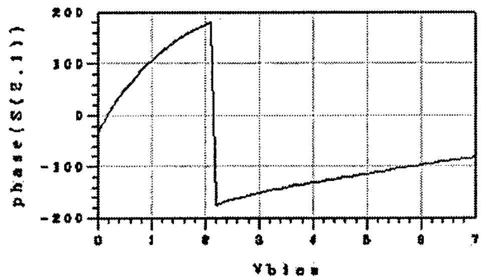
This phase shifter has low pass filter structure and it has cut-off frequency at

$$f_{Bragg} = \frac{1}{\pi \bullet \sqrt{L[C_l + C_d(V)]}}$$

By making its cut-off frequency above 100 GHz using the proper diode size, we can realize as 100 GHz phase shifter. The followings are simulation results for this circuit:



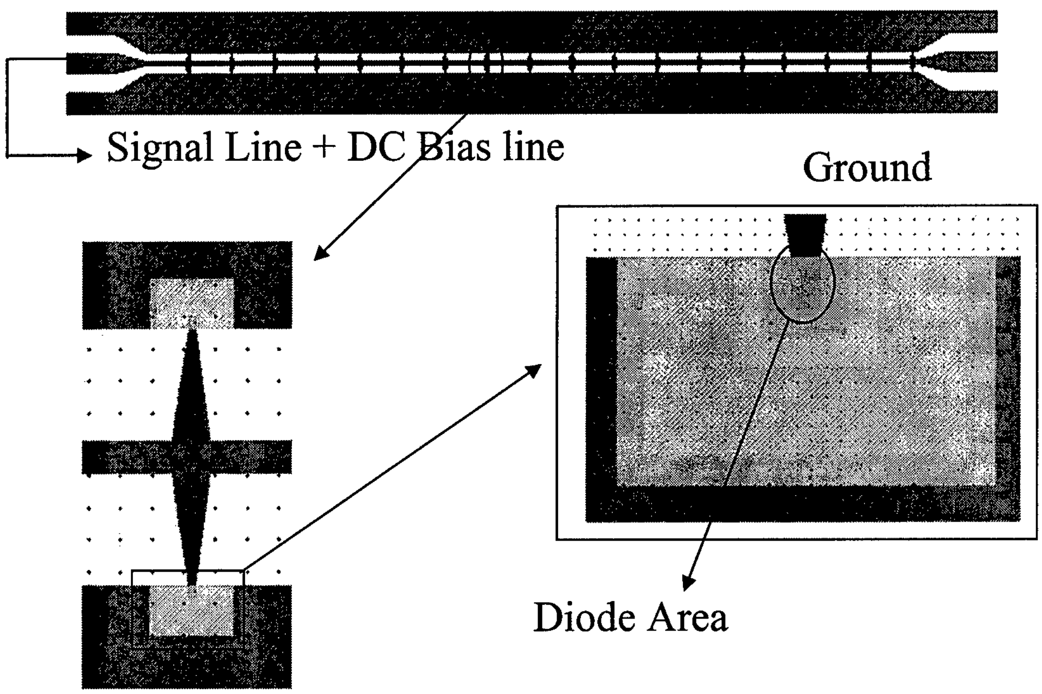
(a) Insertion loss variation for 100GHz phase shifter



(b) output phase variation for 100GHz phase shifter

Fig. 8. 100 GHz Phase Shifter Simulation Results

4.2. Phase Shifter Layout



Status: Circuit will be fabricated using MOS diode structures described above; waiting for epi wafers.

5. LNA (Low Noise Amplifier) Simulation and Fabrication

5.1. LNA Schematic and Simulation Result

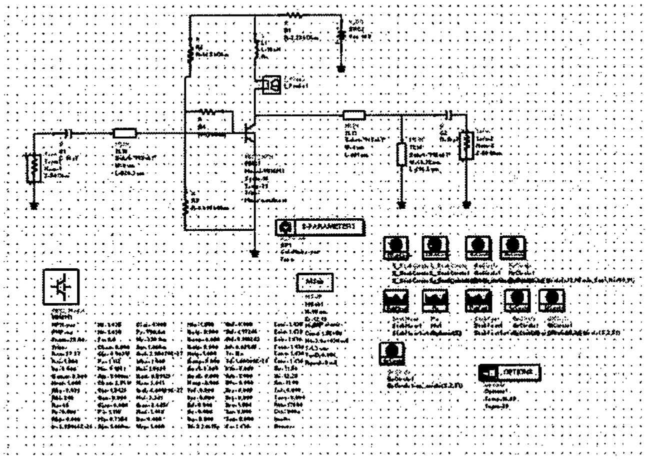


Fig. 10. LNA Simulation Schematic

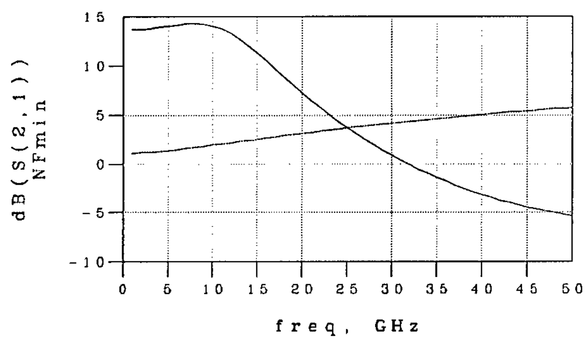


Fig. 11. Simulated results about gain and noise figure

5.2. LNA Chip Fabrication and Measurement

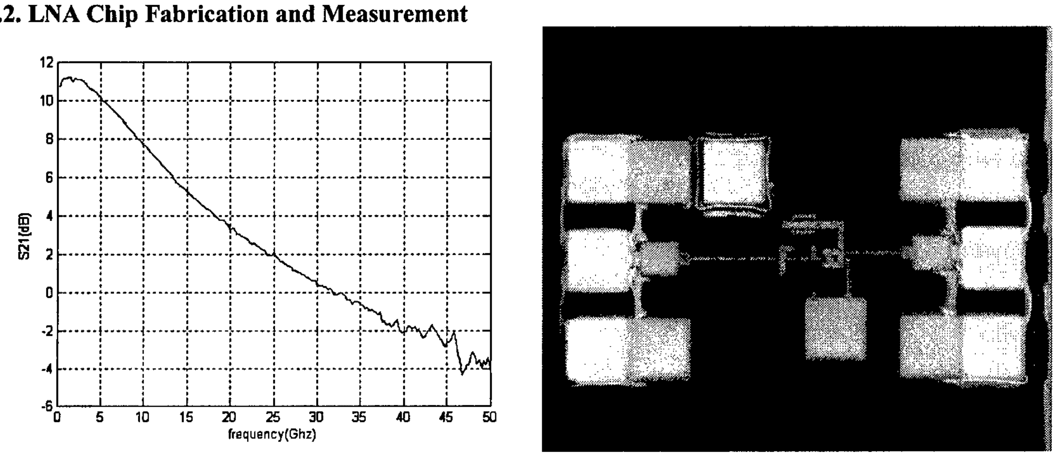


Fig. 12. Measured Gain S_{21} and Chip Photo

Status: project completed.

Personnel supported

(none: this is a DURIP for equipment only)

Publications

(a) Manuscripts submitted, but not published
(none)

(b) Papers published in peer-reviewed journals

S. Bhattacharjee, J. H. Booske, C. L. Kory, D.W. van der Weide, S. Limbach, M. Lopez, R. M. Gilgenbach, S. Gallagher, A. Stevens, and M. Genack, "Folded Waveguide Traveling Wave Tube Sources for THz Radiation," IEEE Transactions on Plasma Science, vol. 32, pp. 1002-1014, 2004

M.K. Choi, K. Taylor, A. Bettermann, and D.W. van der Weide, "Spectroscopy with Electronic Terahertz Techniques for Chemical and Biological Sensing," Chapter 2, Volume II. Emerging Scientific Applications and Novel Device Concepts, Terahertz Sensing Technology, Editors: D. L. Woolard, M. S. Shur and W. R. Loerop, World Scientific, 2003.

D.W. van der Weide, "Electronic Sources and Detectors for Wideband Sensing in the Terahertz Regime," in Sensing with Terahertz radiation, Vol. 85, Springer Series in Optical Sciences, D. M. Mittleman, Ed.: Springer, 2003.

D.W. van der Weide, "Applications and outlook for electronic terahertz technology," *Invited paper* OSA Optics and Photonics News, April 2003.

(c) Papers published in non-peer-reviewed journals or in conference proceedings

M. Genack, S. Bhattacharjee, J. Booske, C. Kory, S.-J. Ho, D. W. van der Weide, L. Ives, and M. Read, "Measurements of microwave electrical characteristics of folded waveguide circuits," presented at Fifth IEEE International Vacuum Electronics Conference, Monterey, CA, 2004.

C. Kory, L. Ives, M. Read, G. Miram, J. Neilson, P. Phillips, J. Booske, S. Bhattacharjee, J. Welter, H. Jiang, D. van der Weide, and S. Limbach, "W-band MEMS-based TWT development," presented at Fifth IEEE International Vacuum Electronics Conference, Monterey, CA, 2004.

J. Welter, J. Booske, H. Jiang, S. Bhattacharjee, S. Limbach, D. van der Weide, N. Zhang, J. Scharer, M. Genack, A. Mashal, C. Kory, L. Ives, and M. Read, "MEMS-microfabricated components for millimeter-wave and THz TWTs," presented at Fifth IEEE International Vacuum Electronics Conference, Monterey, CA, 2004.

D.W. van der Weide, S.-J. Ho, M. Choi, H.-J. Kim, D.-H. Kim, K.-O. Sun, and C.-C. Yen, "OPTIARB: Wideband Optical Arbitrary Waveforms Using Fourier Composition," GOMACTech-03, Tampa, FL, 2003.

D.W. van der Weide, "Detection of chemical and biological hazards with terahertz systems," The terahertz gap: the generation of far-infrared radiation and its applications, Royal Society Scientific Discussion Meeting, London, England, 4-5 June, 2003.

D.W. van der Weide, "Detection of explosives with terahertz systems," Expert workshop on Explosive Detection Techniques for use in Mine Clearance and Security Related Requirements, Lake Bled, Slovenia, 2-4 June, 2003.

M.K. Choi, A. Bettermann, and D.W. van der Weide, "Biological and chemical sensing with electronic THz techniques," presented at Optical Technologies for Industrial, Environmental, and Biological Sensing, Providence, RI, 2003.

(d) Papers presented at meetings, but not published in conference proceedings

D.W. van der Weide, "Terahertz systems for concealed weapons sensing," DSTL Ft. Halstead, UK, 30 September 2003.

D.W. van der Weide, "Terahertz sensing for explosives detection," FOI-Sweden (Swedish Defense Agency), Linköping, Sweden, 29 August 2003

D.W. van der Weide, "Terahertz sensing technology," FFI-Norway (Norwegian Defense Agency), Oslo, Norway, 1 September 2003

D.W. van der Weide, "Spectroscopy with electronic terahertz techniques for chemical and biological sensing," Joint European Research Centre, Ispra, Italy, 12 June 2003

D.W. van der Weide, "Detection of explosives, chemical and biological hazards with terahertz systems," Gordon Conference on Illicit Substance Detection: Explosives, Il Ciocco, Barga, Italy, 8-13 June 2003

Interactions/Transitions

Participation at meetings: Invited to and participated in several international terahertz reviews in Oslo, Linköping, Sweden, the UK and Italy (see above).

Consultative and advisory functions: none during the period

Transitions: Our technology is under consideration for a wide variety of security applications, in both military and civilian venues.

New discoveries: (none this year).

Honors/Awards: (none during the period)